Chapter 19
Glue Line Nondestructive Assessment in Timber Laminates with an Air-Coupled Ultrasonic Technique

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19.1 Introduction

Glued solid wood products have gained much importance during the last years, as they allow an efficient and versatile use of the renewable timber material. Current standardized methods for bonding quality assessment consist of tests of small specimens cut from the structure during production or visual in-service inspection. Ultrasonic diagnostics are traditionally based on discrete point measurements using contact techniques. Transducers are generally pressed onto the timber surface with a coupling gel, liquid, or membrane couplant. Large glue line defects in glued timber constructions have been detected with this method (Dill-Langer et al. 2005). The disadvantages are a low precision in signal level measurements, which are highly dependent on the coupling pressure, and that the coupling agent may deteriorate the object. Better repeatability and one-dimensional continuous scanning is achieved

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with roller transducers, which have been applied to defect inspection in hardwood lumber (Kabir et al. 2002). Non-linear effects have been used to assess delaminations between veneer lamina and particle board (Solodov et al. 2004); a welding piezoelectric stack couples high power ultrasound into the sample and its surface is scanned with a laser vibrometer.

Air-coupled ultrasonics (ACU) provides much more flexibility than traditional techniques since the transducer can be moved at a certain distance from the surface of the object, so fine and reproducible scanning in any direction is possible. A high-power low-frequency ACU system for split detection in wood composites is currently used in production lines (Niemz and Sander 1990). Ultrasonic imaging has been performed in solid wood using through-transmission mode for inspection of density, knots, microcracks and drilled holes (Gan et al. 2005; Hasenstab 2006). Delaminations in wood panel paintings between solid wood and a thin plaster layer have been assessed with both through-transmission and single-sided inspection (Siddiolo et al. 2007).

In this work we present preliminary results of the application of ACU to assess disbonding in glued solid wood objects. A specific measurement set-up and data evaluation based on voltage level measurements of recorded A-scans allows precise imaging of areas with and without adhesive. Advantages and limitations of this method are discussed.

19.2 Theoretical Considerations

The interpretation of the measurements is based on the theory of plane waves in homogeneous isotropic layered media (Brekhovskikh 1980). The sample is modeled as a three layers system, i.e. wood/glue/wood for glued material and wood/air/wood in the case of non-glued material. Due to the high acoustic impedance mismatch between air and solids the pressure level of an ACU signal which propagates through non-glued material is significantly lower than the level for glued material. Only a single echo of a longitudinal wave propagating through the three layers is considered. The acoustic attenuation in the glue line is neglected. It is assumed that the voltage level measured with an ACU transducer is proportional to the force exerted on its surface by ultrasonic waves (Schmerr and Song 2007). A simplified expression for the level ratio is given in Eq. (19.1):

$$L_{\text{glued/non glued}} = 20 \cdot \log_{10} \frac{V_{\text{glued}}}{V_{\text{non glued}}} = T_{\text{wood}\to\text{glue}\to\text{wood}} - T_{\text{wood}\to\text{air}\to\text{wood}}$$

$$T_{1\to 2\to 1} = 20 \cdot \log_{10} \left[\frac{4 \cdot Z_1 \cdot Z_2}{(Z_1+Z_2)^2} \right] \quad Z_i = \rho_i \cdot c_i \tag{19.1}$$

Where: $L_{\text{glued/non glued}}$ (dB) is the amplitude level ratio between ACU signals propagating through glued and non-glued material; V_{glued} (V) and $V_{\text{non glued}}$ (V) are corresponding amplitude measurements in the recorded A-scans. $T_{1\to 2\to 1}$ (dB) is

the transmission coefficient for a single echo propagating through a layer of material 2 between two semi-infinite media of material 1. Z_i (Pa·s/m), ρ_i (kg/m^3) and c_i (m/s) are the acoustic impedance, density and speed of sound in the propagation direction for medium i. From available data $c_{spruce} = 1300$ m/s (measured in T orthotropic direction from ACU data following a similar method to (Vun et al. 2003) and $\rho_{spruce} = 409$ kg/m^3 (gravimetrical determination), therefore $Z_{wood} = 0.532 \cdot 10^6$ Pa·s/m . From literature data (Deutsch et al. 1997) $Z_{glue} = 2.2 \cdot 10^6$ Pa·s/m and $Z_{air} = 0.000427 \cdot 10^6$ Pa · s/m (dry air T = 20°C). From Eq. (19.1) it follows that $T_{wood \to glue \to wood} = -4.1$ dB and $T_{wood \to air \to wood} = -49.9$ dB.

19.3 Material and Methods

19.3.1 Sample Preparation

A total of 46 samples of common spruce (*Picea abies* Karst.) were manufactured in the Wood Physics Laboratory of ETH Zurich; each consisting of two 5 mm thick solid wood lamellas glued together except for some defined areas (Table 19.1). The adhesive is a one-component polyurethane resin (PURBOND® HB 110) applied to one side of the boards with an amount of 200 g/m^2. The boards were pressed together hydraulically during 3 h with a stress of 0.8 N/mm^2. Before the gluing the wood was conditioned to normalized climatic conditions (T = 20°C and RH = 65%), which were afterwards also used for storage.

Only solid wood lamellas with a small percentage of knots, resin pockets, grain distortion, etc. were used in order to analyze the variability of ultrasonic signals propagating through defect free glued timber. The cross-section of the samples is approximately in the orthotropic R-T plane and the curvature of the year rings is negligible (Fig. 19.1).

After ultrasonic measurement, samples of type C and D were broken up and the profile of the transition between glued and non-glued areas was recorded with optical means.

Table 19.1 Geometry of glued timber samples manufactured for ACU measurement

Type	Description
A	Single solid wood lamella of dimensions 500×100×10 mm^3
B	Two lamellas of dimensions 500×100×5 mm^3 glued together to form a glued timber object of 500×100×10 mm^3
C	Same geometry as B. No adhesive applied in the left half area (250×100 mm^2) of the lamellas
D	Same sample type as B. Adhesive only applied in two small areas (about 30×100 mm^2) on the left and right edges of the lamellas

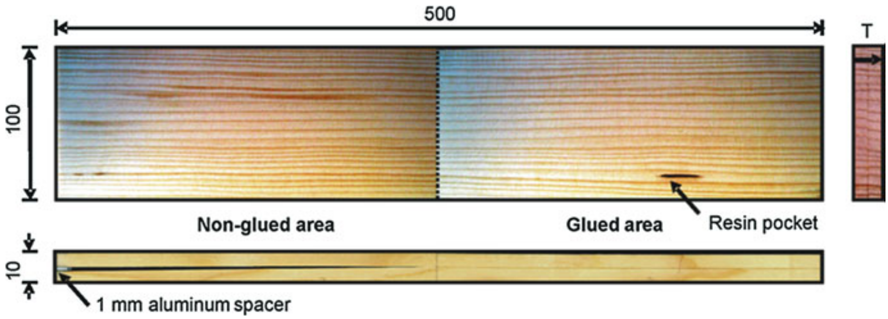

Fig. 19.1 Photographs of external surfaces of a typical C sample. An aluminum spacer of 1 mm thickness on the edge of the non-glued part allows control of the gap thickness. The year ring angle varies between 90º (propagation in orthotropic T direction) and 45º. Small defects like a 26 mm long resin pocket were allowed

19.3.2 Experimental Setup

The measurement setup is shown in Fig. 19.2. Two ACU broadband planar transducers (model NCG100-D50, The Ultran Group) with a central frequency of 120 kHz and 50 mm active diameter were aligned perpendicularly to the surfaces of the sample, one transmitting an ultrasonic signal and the other one receiving it. The distance between the transmitter and the sample (210 mm) was chosen to minimize the diameter of the sound field penetrating the latter. A three-axis system from ISEL® moves the two transducers together as a fixed unit; scanning the surface of the samples with steps of 1 mm in the fast axis and 4 mm in the slow axis. A sinusoidal pulse of 115 Vpp amplitude and 33 μs length windowed with a Gaussian function was applied to the transmitter. Received waveforms were amplified with a gain of 52 dB and digitized with a sampling frequency of 2.5 MHz and 14 bits resolution, the generated A-scans being stored for each scanned position. No averaging of A-scans was performed. C-scans were generated from a peak or root mean square (RMS) voltage measurement for each A-scan and a defined time gate $[t_1, t_2]$:

$$V_{\mathrm{PEAK}} = \max_{[t1,\, t2]} V(t) \quad V_{\mathrm{RMS}} = \sqrt{\frac{1}{t_2 - t_1}\int_{t1}^{t2} V(t)^2 dt} \tag{19.2}$$

The distance between receiver and sample (80 mm) allows separating in time multiple reflections between their surfaces (3) from measured waves (1) and (2). A-scans received through bonded material (1) present a signal-to-noise ratio of 55 dB, which allows for enough dynamic range to record waveforms from glued and non-glued areas in a single scan. Waves diffracted at the edges of the sample (4) are blocked by a frame built around the inspected object. The frame is made from wood (Norway spruce) covered by several layers of paper with small gaps of air

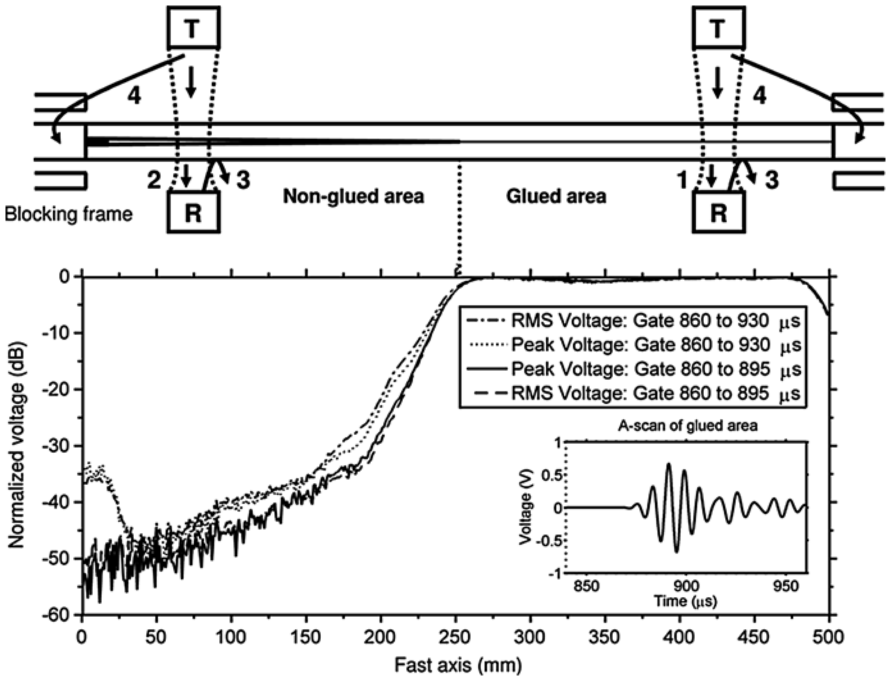

Fig. 19.2 Experimental set-up. *Top image*: Inspection principal and main propagation paths. 1 and 2 are waves propagating through the sample for glued and non-glued areas respectively. 3 are multiple reflections between the receiver and the surface of the sample. 4 are waves diffracted at the edges of the sample, which are blocked by a frame built around the object. The noise level in the A-scans is 1.3 mV_{RMS}. *Bottom image*: Profile of voltage level along the fast axis normalized with respect to the glued area. The gap thickness decreases linearly between fast axis 0 and 250 mm from 1 mm down to the glue line thickness

in between. Waves propagating through the frame are highly attenuated due to the accumulation of impedance mismatch losses.

19.4 Results and Discussion

19.4.1 Imaging of Glue Presence and Repeatability of Measurements

Figure 19.3 demonstrates successful ultrasonic imaging of absence and presence of adhesive of a typical glued timber sample of type C, which corresponds to the object photographed in Fig. 19.1. As expected, there is a strong voltage reduction in the left area of the board surface, corresponding to the non-glued region. The transition between glued and non-glued areas could be imaged accurately. Figure 19.4 shows an ultrasonic image of a sample type D, in this case the two glued areas on the left

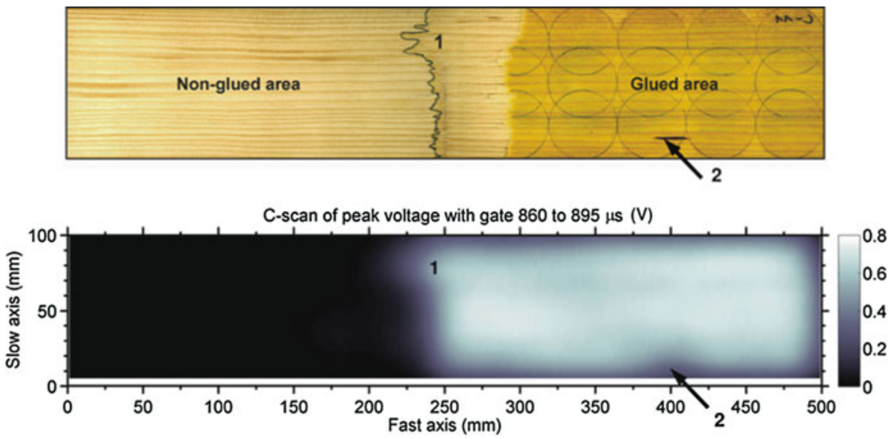

Fig. 19.3 ACU imaging of glue presence for the sample in Fig. 19.1. *Top image*: Photograph of open board; the transition between glued and non-glued area is highlighted. *Bottom image*: ACU C-scan of the sample. Feature 1 of the transition between glue/no glue and the resin pocket (2) can be visualized

and right sides of the surface of the image can be clearly distinguished; the amplitude values being higher than the ones measured in non-glued areas. In both images, details of the transition between glued and non-glued regions can be resolved. The spatial resolution of the images is limited by the sound field diameter (about 35 mm); features smaller than 20 mm cannot be resolved. Preliminary tests applying spatial deconvolution algorithms to the ultrasonic images showed an improvement of the resolution limit down to 10 mm.

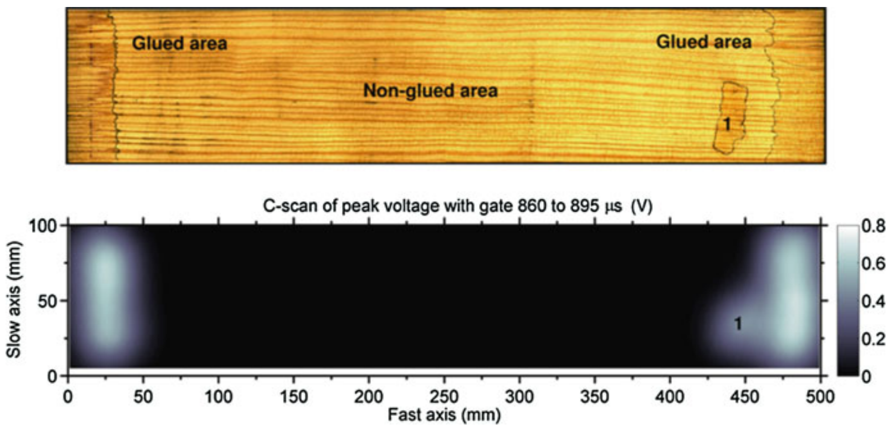

Fig. 19.4 ACU imaging of glue presence and absence of a sample type D. *Top image*: Photograph of open board; in this case there was a small drop of glue (feature 1) joining the two lamellas, separated from the glued area on the right side of the sample. *Bottom image*: ACU C-scan. The presence of the drop of glue can be clearly recognized; however, the non-glued area between feature 1 and the glued region on the right side is smeared by the finite diameter of the sound field

Figure 19.2 shows in logarithmic scale the voltage level variations between glued and non-glued area for a typical fast axis amplitude profile of a sample type C, and for specific air gap thicknesses between the two lamellas. The voltage level in the non-glued area shows a minimum of –50 dB with respect to the glued area, in good agreement with the estimation for $T_{wood \to air \to wood}$. As the gap thickness between boards decreases, this level rises due to multiple reflections of the ultrasonic wave adding constructively in the gap. About 20 mm from the boundary to the glued area propagation through bonded material becomes dominant, owing to the finite diameter of the sound field. An amplitude rise is observed in the delaminated area from fast axis 0 to 50 mm. It probably corresponds to residual ultrasonic energy diffracting through air at the edges of the sample, which is not blocked by the frame.

Best measurement performance was achieved by limiting secondary ultrasonic propagation paths by evaluating a reduced number of cycles at the beginning of the received waveform. RMS voltage and peak voltage give similar results with sufficiently short temporal gates (less than 40 μs). Repeated ACU measurements of the same object showed variations of less than 0.1 dB (error < 1%).

A homogenous amplitude level was observed in the ACU images of samples type A and B. The average voltage level measured for type B glued samples is –1 dB with respect to the value for type A solid wood samples; a smaller difference than predicted by $T_{wood \to glue \to wood}$, which further enhances the contrast of ACU images. A probable reason is the constructive interference of multiple reflections of the ultrasonic wave in the glue line.

19.4.2 Influence of Natural Variability and Anisotropy of Wood

Wood inhomogeneity introduces variations of up to 8 dB in voltage measurements of glued material without compromising the detectability of non-glued areas. Due to the small uncertainty of ACU measurements specific wood structure features can be visualized in the C-scans. Regions with highest latewood concentration show lowest voltage levels. A possible reason is the fact that latewood has higher acoustic impedance than earlywood and therefore larger impedance mismatch with air. Small defects in the material decrease the measured voltage, since they scatter partially the ultrasonic field; for instance, a resin pocket can be visualized in Fig. 19.3. Variations of the year ring angle could not be correlated to voltage amplitude changes in a clear fashion, an indication that the influence of anisotropy is not large for the inspected objects.

19.5 Conclusion

We have demonstrated that air-coupled ultrasound is well-suited for glued timber inspection; combining the high sensitivity to disbonded interfaces of traditional ultrasonic methods with a phenomenal reproducibility in amplitude measurements,

and precise spatial data acquisition. Moreover it is a fully non-invasive method, since no couplant is required between transducers and sample. Current state-of-the-art transducers plus moderate pulser voltage and receiver gain allow transmission through 10 mm thick glued timber samples with a signal-to-noise ratio of 55 dB; therefore inspection of thicker objects is promising. The repeatability error is smaller than 1%. A through-transmission measurement set-up achieves level variations of up to 50 dB between glued and non-glued material, which ensures a reliable glue line assessment despite amplitude variations of up to 8 dB in bonded regions, due to the heterogeneity of the wood structure.

Future research work is planned to inspect thicker (over 10 cm) multiple laminated glued timber. The main challenge is to resolve small amplitude level variations between bonded and disbonded areas from larger level variations within bonded material (higher influence of natural variability and anisotropy).

19.6 Summary

Wood is a sustainable construction material. Glued timber products make efficient use of the strength properties of solid wood; moreover, structural members of expanded dimensional and geometrical properties can be produced. The integrity of the glue lines of timber laminates needs to be assessed during the full life cycle of the product; therefore, a non-destructive reproducible inspection method is required. As part of an ongoing project, we performed air-coupled ultrasound (ACU) measurements in glued timber laminates. A normal transmission setup with 120 kHz commercial transducers was used to analyze samples consisting of two spruce solid wood lamellas glued together with polyurethane adhesive introducing defined delaminated areas. Ultrasonic scanning with high resolution was performed to successfully image the presence or absence of glue. The geometry of the delaminated regions and features of the wood structure could also be visualized. We have demonstrated that ACU is a sensitive, accurate, reproducible and non-invasive inspection alternative with respect to conventional contact techniques; therefore, it is well-suited for glued timber inspection. Future work is planned for the inspection of more complex glued timber structures.

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References

Brekhovskikh LM (1980) Waves in layered media. New York, NY, Academic

Deutsch V, Platte M, Vogt M, Verein Deutscher Ingenieure (1997) Ultraschallprüfung Grundlagen und industrielle Anwendungen. Springer, Berlin

Dill-Langer G, Bernauer W, Aicher S (2005) Inspection of glue-lines of glued-laminated timber by means of ultrasonic testing. In: Proceedings of the 14th international symposium on nondestructive testing of wood. Eberswalde, pp 49–60

Gan TH, Hutchins DA, Green RJ, Andrews MK, Harris PD (2005) Noncontact, high-resolution ultrasonic imaging of wood samples using coded chirp waveforms. IEEE Trans Ultrason Ferroelectr Freq Control 52(2):280–288

Hasenstab A (2006) Integritaetspruefung von Holz mit dem zerstoerungsfreien Ultraschallechoverfahren.Technische Universitaet Berlin. PhD Thesis

Kabir MF, Schmoldt DL, Schafer ME (2002) Time domain ultrasonic signal characterization for defects in thin unsurfaced hardwood lumber. Wood Fiber Sci 34:165–182

Niemz P, Sander D (1990) Prozessmesstechnik in der Holzindustrie. VEB Fachbuchverlag, Leipzig

Schmerr LW, Song SJ (2007) Ultrasonic nondestructive evaluation systems models and measurements. Springer, New York, NY

Siddiolo AM, D'Acquisto L, Maeva AR, Maev RG (2007) Wooden panel paintings investigation: an air-coupled ultrasonic imaging approach. IEEE Trans Ultrason Ferroelectr Freq Control 54(4):836-846

Solodov I, Pfleiderer K, Busse G (2004) Nondestructive characterization of wood by monitoring of local elastic anisotropy and dynamic nonlinearity. Holzforschung 58:504–510

Vun RY, Wu QL, Bhardwaj MC, Stead G (2003) Ultrasonic characterization of structural properties of oriented strandboard: a comparison of direct-contact and non-contact methods. Wood Fiber Sci 35(3):381–396